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KINETICS IN JUMPING REGARDING AGILITY DOGS

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ABSTRACT

Canine agility is a popular sport discipline, involving various jumping activities. Handlers navigate their dogs through a course with different obstacles. Courses are characterized by jumping at high speed and with fast directional changes. Systematic scientific research regarding kinetics in jumping agility dogs is scarce. For the first time, we examined kinetic parameters for single legs in take-off and landing a hurdle jump. Further, we compared straight jumps and wrap jumps, where dogs perform a tight turn during the landing phase.
Simultaneous kinetic and kinematic data were recorded from 10 advanced agility Border collies jumping over two consecutive hurdles. We here report the jump kinetics. Ground reaction forces (GRF) were recorded for hindlimbs during take-off and forelimbs during landing.
For straight jumps, we found synchronous hindlimb touchdown at take-off phase. Ground reaction force shows similar GRF progression in both hindlimbs. During the landing of a straight jump, the forelimbs show skipping gait pattern, with first touchdown of the trailing limb, followed by touchdown of the leading limb. We found shallower angle of attack and a higher decelerative impulse for the leading limb than the trailing limb.
For wrap jumps, hindlimbs touchdown was synchronous during the take-off phase, but the GRF pattern differed. The GRF progression indicated that the take-off pattern of the two limbs acts like a differential gear. Hindlimbs produced a torque already at take-off, to start the wrap.
The touchdown of forelimbs was synchronous during landing, but like the hindlimbs they showed a different GRF progression. We found longer contact durations for the left than the right forelimb. Peak vertical and mediolateral forces seem to be higher for the right forelimb than the left forelimb, to resist inertia effects and to continue turning.

1. INTRODUCTION

Agility is a canine sport discipline that is becoming increasingly popular. In this sport handlers navigate their dogs through a course with different obstacles in the shortest time and without faults. Most of the obstacles are hurdle jumps, set at a predetermined height in relation to the dog's height at the withers, see Table 2 categorization rules of the Fédération Cynologique Internationale (FCI). The dog's success depends on its ability to jump at high speed and with rapid directional changes [1]. In the large category, there is a majority of collie breeds, not at least by virtue of their intelligence, speed and versatility [2]. Further, the dogs's skill is categorized by a grading system (Table 1).
Compared to the growing popularity of this sport, there is relatively little research done regarding kinetics of jumping in dogs. Reports show, that one-third of agility dogs has become injured, with 58 % of injuries occurring during competition [3]. Levy et al. as well as Cullen et al. reported that there is a higher risk of injuries for Border collies, than other breeds. This is maybe related to the high rates of speed. Furthermore Cullen et al. reported that longer experience in agility of the handlers and their dogs may significantly reduce the risk of injuries. With increased deliberate practice, it is possible that dogs become more accurate, find a safer obstacle performance and a better decision making, thus exposing themselves to lower risk [4].

According to the research of steady-state gait in dogs [5-10], even less research has been done on dynamic activity. Cause of varying key locomotor parameters between subsequent strides, jumping can be contemplated as non-steady-state activity.
Yanoff et al. found that vertical ground reaction forces increased with increasing obstacle height and increasing body mass [11]. Pfau et al. reported that an increase of hurdle heights results in a lower approach speed and more acute landing angle. The kind of obstacles and distance between them showed difference for peak vertical force, vertical impulse and accelerative horizontal impulse [1]. However, none of these authors reported single leg reaction forces in jumping dogs. No research has been done to investigate jumping parameters for wrap jumps.
The aim of this study was to quantify the main kinetic parameters observed during take-off and landing phase for each single leg for jumping in a straight direction (below referred as straight jump) in comparison to jumping over the hurdle with making a tight turn to the left while landing (below referred as wrap jump).

Table 1: Level of skill defined under *Fédération Cynologique Internationale* FCI regulations

Grade	**Ability**	**Progression**
A1	Beginner	Companion dog test passed, age about 18 months
A2	Novice	Dogs that won three times A1 top-seeded, or five times faultless
A3	Advanced	Dogs that won three times A2 top-seeded, or five times faultless

Table 2: Jump height categories under Fédération Cynologique Internationale (FCI) regulations

Category	**Height at the withers**	**Jump height**
Small	< 350 mm	350 mm
Medium	351 mm – 430 mm	450 mm
Large	> 431 mm	650 mm

2. METHODS

2.1 Animals

We obtained kinematic and kinetic data from ten healthy adult Border collies weighing 18.7 kg ± 3.6 kg. They were all categorized as large with a height at the withers of 53.6 cm ± 3.6 cm. All dogs are competing at advanced level (A3) and had experience for more than 4 years of experience in agility, their handlers had at least 5 years of experience.

2.2 Motion capturing

Kinematic data were recorded with an optoelectronic marker based method. Sixteen infrared cameras (Oqus Series 300, 400, Qualisys, Göteborg) were set around the walking track. The animals were recorded at a frequency of 400 Hz, using Qualisys Track Manager® software (QTM, Version 2.15, Qualisys, Göteborg). A standard wand based calibration procedure resulted in a calibrated area of approximately 6 x 6 x 1.5 m (length x width x height) with a calibration error (standard deviation of the wand length) of below 3 mm. This calibration procedure resulted in the creation of a right handed Cartesian coordinate system (negative x-axis in the direction of the progression of the dogs, z-axis upwards and y-axis to the left). Animals were prepared with 83 passive markers based on [12]. Markers were attached to the shaved skin with double-sided adhesive tape. Additional we used Kinesiotape® for fix the markers at the proximal parts of the legs. Body markers were additionally fixed with a flexible stretch tube.

2.3 Force data acquisition

We measured three-dimensional ground reaction forces (GRF) with eight force plates (600 mm x 900 mm, 9287 CA, Kistler Instruments AG). Two rows of each four force plates were integrated into the walking-track. Each plate was covered up with a tartan mat to have a slip-proof surface. GRF was sampled at 2 kHz, synchronized with the kinematic recording.

2.4 Data collection and procedure

Two hurdles compliant to the FCI rules were used. Both were set 90 % at the dog's height at the withers. Dogs had to start 4 meters in front of the first hurdle. The distance between the hurdles was 5 meters. After the second hurdle, dogs had a minimum of 4 meters for runout. The second hurdle was placed over the force plates without contacting them. For take-off and landing the hurdle was placed such, that each limb touched a separate force plate. Due to the long jumping distances and the length of the force plates, take-off and landing had to be recorded in different trials.

For the wrap jump the dogs made a tight turn to the left after jumping across the hurdle after which they run back to start position. We recorded the data for the wrap jump in the same manner as the straight jumps. Each dog was led by their owner, using their preferred technique, see Figure 1and Figure 2. The goal was to record five valid trials per jump configuration, depending on the dog's motivation and ability. A valid jump was made if:

- the dog jumped across both hurdles without knocking down the pole
- either, the dog took off with both hindfeet on different force plates, or
- the dog landed with both front feet on different force plates

The dog and handler were acquainted with the task. Body weight (BW) was measured while the dog was standing still on one force plate. Dogs were given rests whenever the handler or the experimenter judged it appropriate. The order of the trials was: take-off straight jump, followed by landing straight jump, take off wrap jump and finally landing wrap jump.

2.5 Data analysis

Kinematic data were processed using QTM. For each foot a rigid body (6DOF) was calculated, whose local coordinate system was defined from the recording of the dog's weight, with the positive x-axes in direction of progression of the dog, z-axis positive upwards and y-axis perpendicular to x- and z-axis, positive to the left. Body coordinate systems were used to rotate force data along the z-axis. To make data comparable force and impulse parameters were normalized to BW. Parameters were also normalized to the time of foot contact, which was calculated individually for each limb and trial. Due to nearly synchronous touchdown of the limbs we differentiate between left (LH) and right (RH) hindlimb for take-off in both directions. For landing the wrap jump we differentiate between left (LF) and right (RF) forelimb. Only for landing phase of the straight jump we decided to differentiate between the trailing (TrF) and the leading (LdF) forelimb, where the first touchdown is made by the trailing limb and second touchdown by the leading limb.

All data were analyzed using MATLAB® 2017a.

A one-way analysis of variance (ANOVA) was performed to investigate the difference between the limbs and differences between straight and wrap jumps.

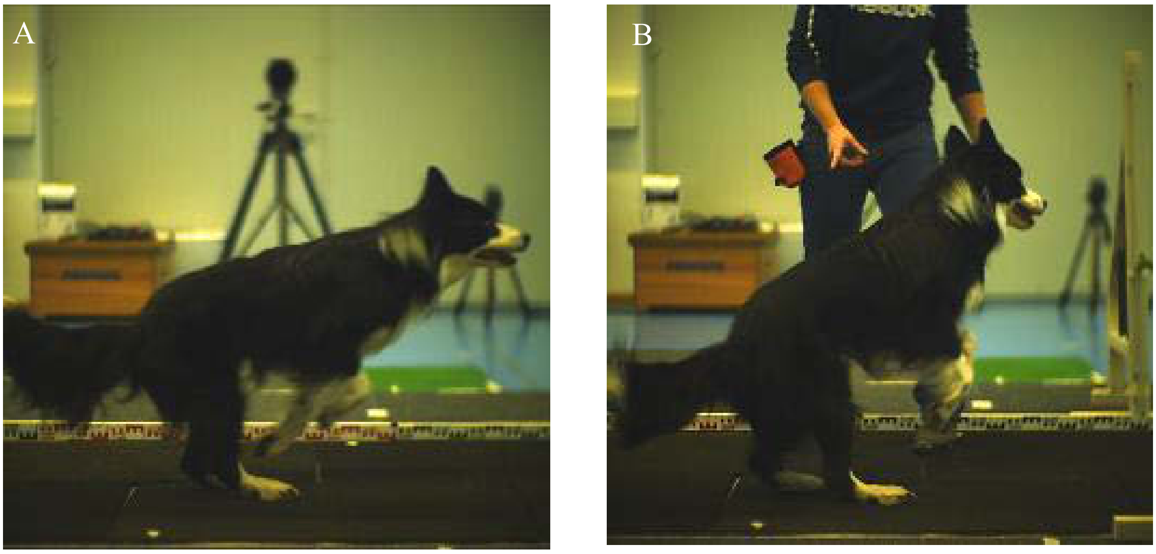

Figure 1: A: Take-off straight jump; B: Take-off wrap jump

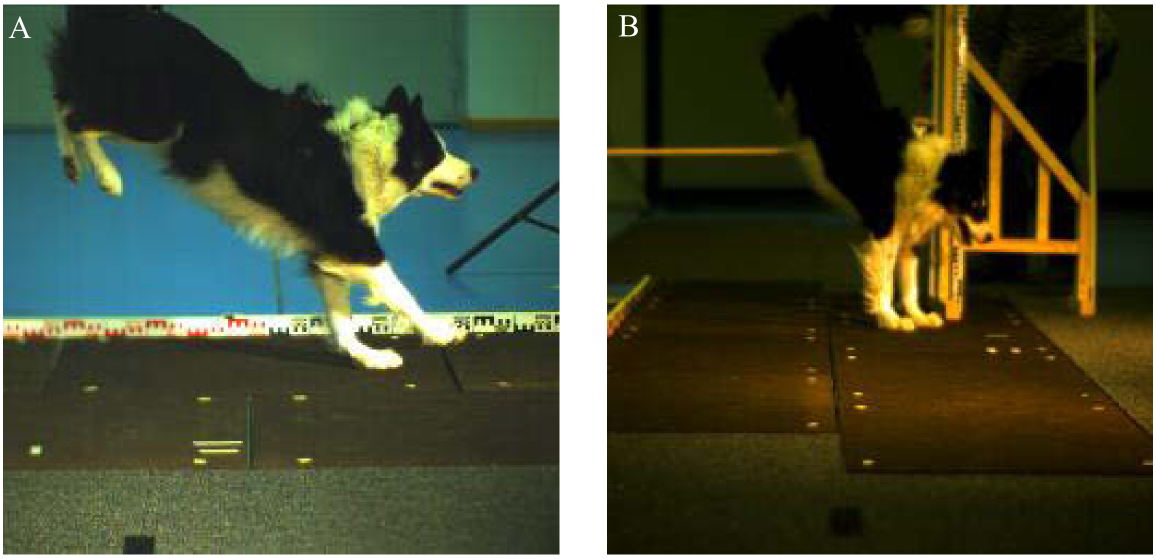

Figure 2: A: Landing straight jump; B: landing wrap jump

3. RESULTS

In total, 176 trials were analyzed from the 10 subjects. We analyzed minimum two trials for any condition in all dogs.

3.1 Contact Time

Table 3 shows the averaged contact time and standard deviation for each leg at the two jump configurations. There are no significant differences between the hindlimbs and between the forelimbs for the straight jump. In contrast during the wrap jump the time of contact for take-off and landing is significant longer for each limb. Forelimbs show longer stance time than hindlimbs and the left forelimb shows longer stance time than the right forelimb ($p < 0.001$).

Table 3: Contact time in ms for each leg at the different jump configurations. LH, left hindlimb; RH, right hindlimb; LF, left forelimb (wrap jump); RF, right forelimb (wrap jump); TrF, trailing forelimb (straight jump); LdF, leading forelimb (straight jump).

Phase	**Take-off**		**Landing**	
Limb	LH	RH	LF or TrF	RF or LdF
Straight jump	88 ms ± 15 ms	87 ms ± 12 ms	87 ms ± 8 ms	90 ms ± 8 ms
Wrap jump	133 ms ± 19 ms	131 ms ± 16 ms	192 ms ± 35 ms	161 ms ± 19 ms

3.2 Force and impulse

3.2.1 Take-off

Figure 3 shows averaged vertical (F_z), craniocaudal (F_x) and mediolateral (F_y) force–time plots during taking off from a straight hurdle jump (panel A and B). Vertical force shows symmetrical progression. The maximum of the vertical force was reached at nearly 40 % of the contact duration. Peak vertical force (LH 1.6 BW ± 0.3 BW; RH 1.8 BW ± 0.3 BW) was not significantly different between the two hindlimbs ($p = 0.066$). Craniocaudal force changed from decelerative to accelerative force at nearly the half of the contact for both hindlimbs. Due to the body-fixed coordinate system mediolateral force (F_y) is counter-rotating in both hindlimbs, but in medial direction for both hindlimbs.
The vertical impulse was different for both hindlimbs ($p = 0.02$), with higher impulse for the right hindlimb (mean over the contact phase: LH 0.09 BW ± 0.01 BW; RH 0.10 BW ± 0.02 BW) (cf. Figure 4). No significant difference was found for both hindlimbs, neither in accelerative (LH 0.008 BW ± 0.004 BW; RH 0.008 BW ± 0.005 BW), nor in decelerative impulse (LH -0.006 BW ± 0.003 BW; RH -0.008 BW ± 0.004 BW), ($p = 0.98$; $p = 0.065$).
In contrast, Figure 3 shows the force-time plots at taking off before jumping a tight turn to the left. Vertical force rose to a plateau, with significant different peak vertical forces (LH 1,1 BW ± ,02 BW; RH 1,4 BW ± 0,3 BW). Mediolateral force was directed inwards during the wrap jumps and the plateau is higher and expanded for the right limb than for the left limb. While left hindlimb shows only negative craniocaudal force, right hindlimb changes from decelerative to accelerative force at nearly half of the contact time. Significant differences between the two legs were also seen for vertical impulse (mean over the contact phase: LH 0.096 BW ± 0.019 BW; RH 0.121 BW ± 0.02 BW), accelerative impulse (mean over contact time: LH 0.0002 BW ± 0.0005 BW; RH 0.006 BW ± 0.005 BW) and decelerative impulse (mean over contact time: LH -0.02 BW ± 0.009 BW; RH -0.01 BW ± 0.008 BW), (all $p < 0.001$; cf. Figure 4, Figure 5).
Differences between the jumping configuration were significant for peak vertical force in both hindlimbs ($p < 0.001$). Significant differences were found between both configurations for accelerative impulse and decelerative impulse in the left hindlimb, and vertical impulse in the right hindlimb (all $p < 0.001$).

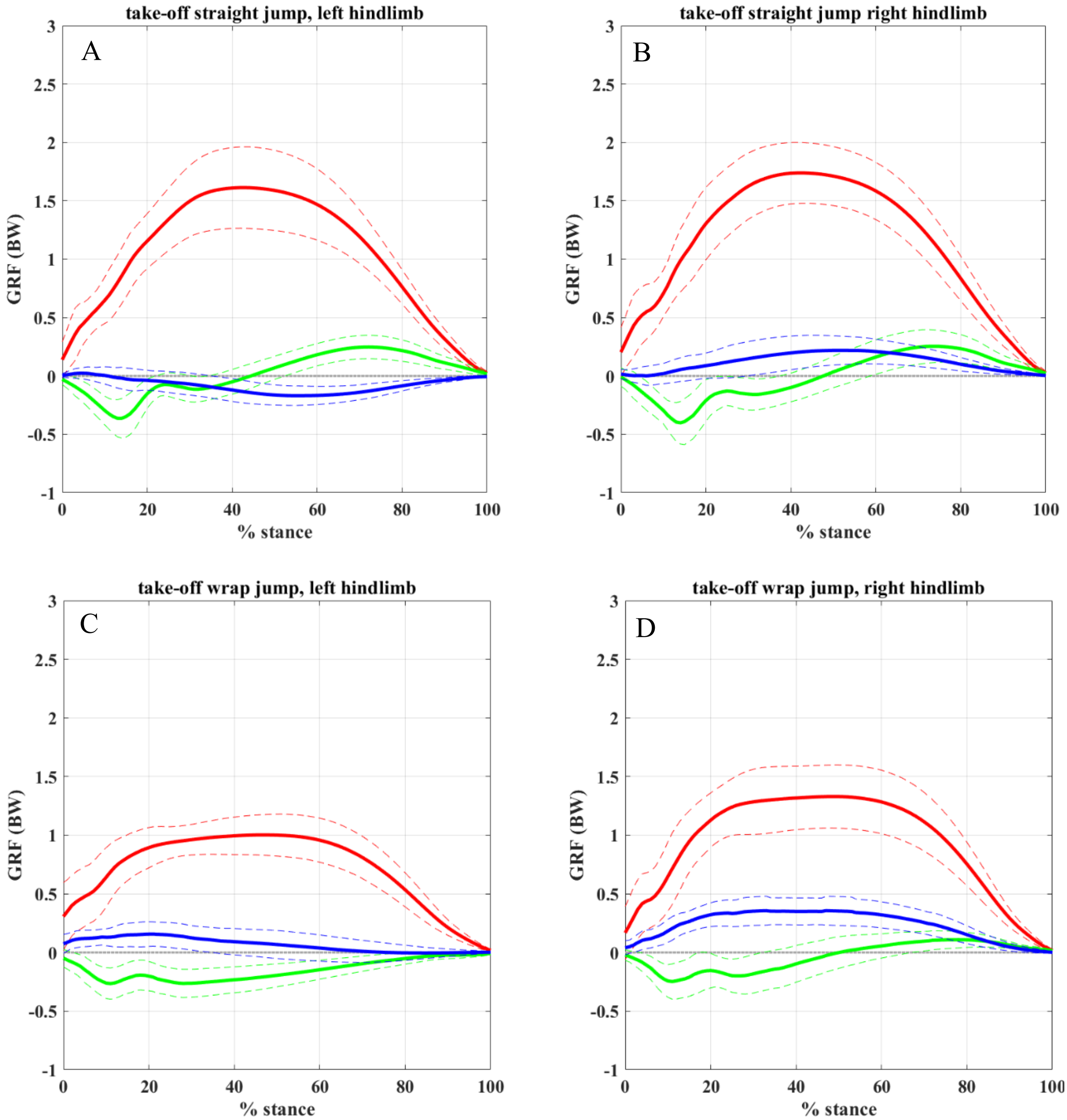

Figure 3: Averaged force-time plots of straight jump (A, B) wrap jump (C, D). Red: vertical (F_z), Green: craniocaudal (F_x), Blue: mediolateral (F_y) force-time plots of the left hindlimb (A, C) and the right hindlimb (B, D). Dashed: standard deviation. Note that force was normalized body weight and plotted over normalized contact time.

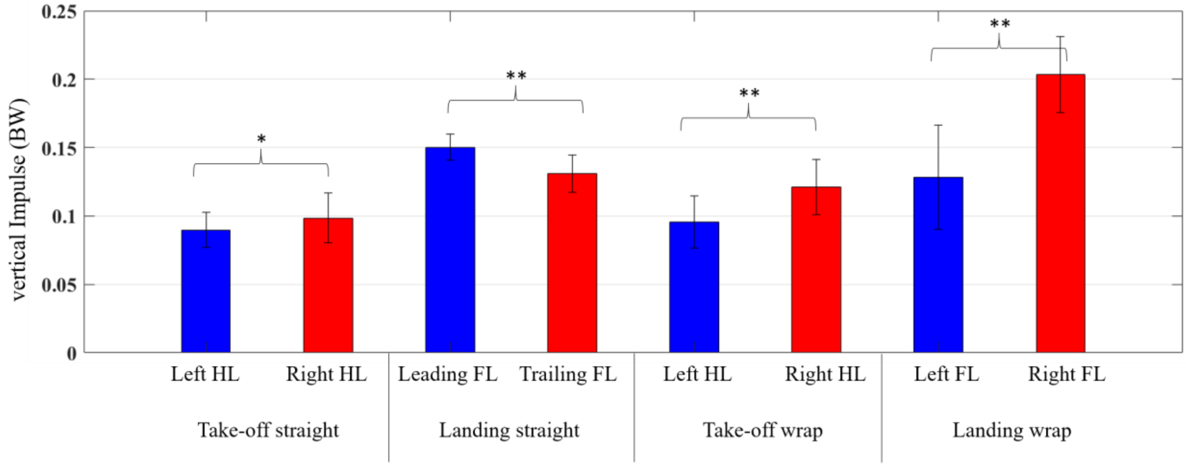

Figure 4: Vertical Impulse of the four jumping configurations. Blue: left and leading limbs. Red: right and trailing limbs. * significant different with $p < 0.05$; ** significant different with $p < 0.001$

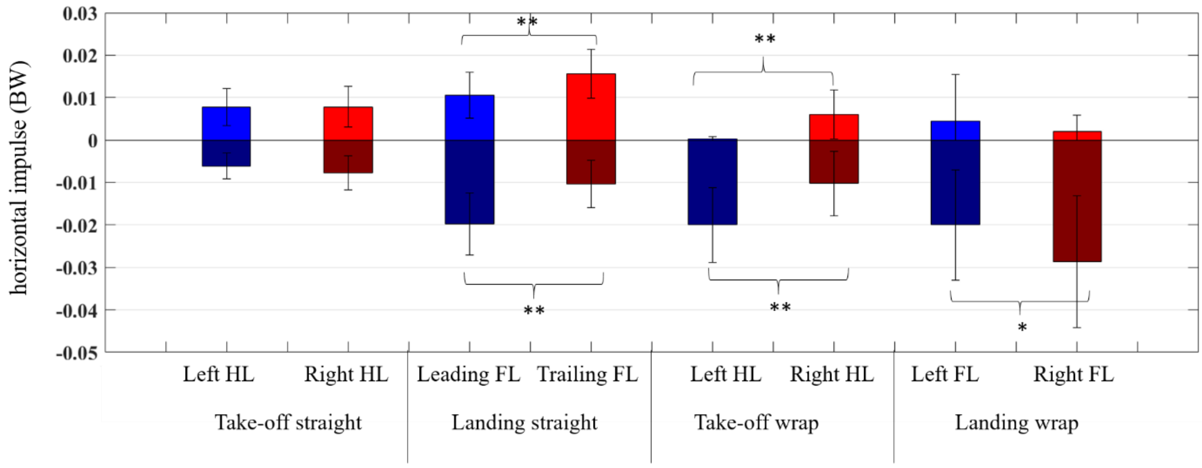

Figure 5: Averaged accelerative impulse (light) and decelerative impulse (dark) for each limb at the four trials. Blue: left and leading limbs. Red: right and trailing limbs. * significant different with $p < 0.05$; ** significant different with $p < 0.001$

3.2.2 Landing

Figure 6 (A, B) shows average vertical (F_z), mediolateral (F_y) and craniocaudal (F_x) force–time plots for landing a hurdle jump in a straight direction. Vertical force in the trailing limb rises till circa 50 % of the contact period, where peak vertical force is reached (Tr 2.47 BW ± 0.27 BW). The leading limb reaches peak vertical force at 40 % of stance (Ld 2.5 BW ± 0.24 BW). There was no significant difference between the two forelimbs in vertical peak force ($p = 0.53$). Craniocaudal force changed from decelerative force to accelerative force earlier in the trailing than in the leading limb.

Significant difference in vertical impulse were found between the two forelimbs ($p < 0.001$), (mean over the contact phase: LdF 0.15 BW ± 0.009 BW; TrF 0.131 BW ± 0.013 BW), see Figure 4. The difference in accelerative impulse (mean over contact phase: LdF 0.011 BW ± 0.005 BW; TrF 0.016 BW ± 0.006 BW) and decelerative impulse (mean over contact phase: LdF -0.02 BW ± 0.007 BW; TrF -0.01 BW ± 0.006 BW) is likewise significant ($p < 0.001$) between the two limbs (Figure 5).

Figure 6 (C, D) shows averaged GRF for the left and right forelimb. Vertical force in the right limb rise till 30 % of contact duration. The peak vertical force in the right limb (RF 2.04 BW ± 0.29 BW) is significant higher in comparison to the left forelimb (LF 1.02 BW ± 0.22 BW), ($p < 0.001$). Mediolateral force shows similar progression like vertical force with lower

amplitude. Craniocaudal force in both forelimbs is negative for largely part of the contact period. Vertical impulse is also significant higher for the right forelimb (mean over the contact phase: LF 0.128 BW ± 0.038 BW; RF 0.203 BW ± 0.027 BW) ($p < 0.001$).
The forelimbs show higher decelerative impulse than accelerative impulse. Both forelimbs show significant difference in decelerative impulse (mean over contact phase: LF -0.2 BW ± 0.013 BW; RF -0.029 BW ± 0.015 BW) ($p = 0.0027$). No significant difference in forelimbs was found for the accelerative impulse (mean over contact phase: LF 0.005 BW ± 0.01 BW; RF 0.002 BW ± 0.004 BW) ($p = 0.22$), (cf. Figure 4, Figure 5).

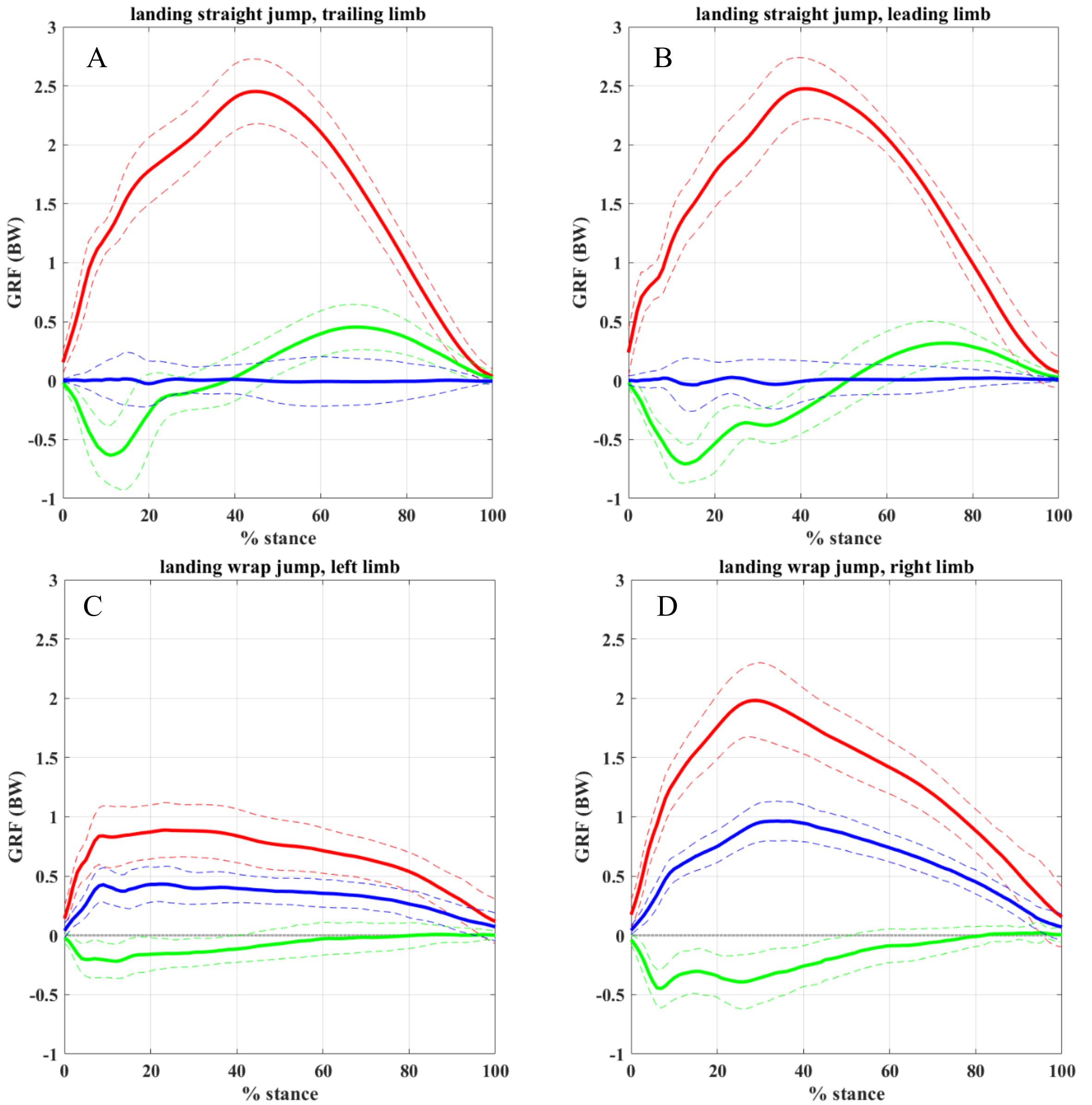

Figure 6: Force-time plots for landing a straight jump (A, B) and a wrap jump (C, D). Red: Averaged vertical (F_z), green craniocaudal (F_x) and blue mediolateral (F_y) force-time plots of the trailing (A), leading (B) forelimb and the left (C) and right (D) forelimb. Dashed lines: standard deviation. Note that force was normalized body weight and plotted over normalized contact time.

4. DISCUSSION

This study presents, for the first time, single leg GRF profiles for the hindlimbs at take-off and the forelimbs at landing during straight and wrap jumps. The outcome of a jump largely depends on the approach and take-off phases [13].

For the straight jumps, in most cases the hindlimbs touch the ground synchronously at take-off phase and feet were placed parallel. Both hindlimbs showed almost identical GRF profiles. Our findings corroborate with [14], in that the craniocaudal forces were predominantly propulsive. Mediolateral forces were orientated towards medial. Dogs spread their hindlimbs at touch down and placed feet lateral to the body midline. The net force vector of the mediolateral forces acts directly through the midline.

Landing forces were absorbed by the forelimbs as reflected by the high peak amplitudes of the vertical forces. For landing a straight jump, forelimbs touched the ground one after the other. First touchdown was made by the trailing limb and second touchdown by the leading limb, as already described for horses [15-17]. Immediately before impact, the trailing forelimb reaches an angle of attack 77.8 ° ± 3.7 °, while the leading forelimbs' angle of attack was 66.7 ° ± 4.0 °. Decelerative impulse can only be generated while the foot is in front of the upper pivot of the spina. Stepper angles of attack do not permit to generate larger breaking forces. might the reason why the leading limb is able to exhibit a higher decelerative impulse. These findings are similar to those obtained for jumping horses [14, 17, 18] and skipping gaits [19, 20]. The bipedal spring loaded inverted pendulum template (BSLIP), used by Andrada et. al showed that peak vertical force is related to leg stiffness and foot-placement strategy. On average, we found no significant difference in the peak vertical forces between the forelimbs, which is in agreement with findings in horses [17]. However, individual trials show that there may be differences up to 50 % of BW in the peak vertical forces values between trailing and leading limbs. We found trials with higher as well as equal and lower peak vertical force for the trailing than for the leading limb. These differences, as described by Andrada et al. might be explained by the leg stiffness. In simulations, an increased leg stiffness in the trailing limb resulted in higher peak vertical forces in the trailing limb and decreased peak vertical forces for the leading limb and vice versa [19]. We found angle of attack, that for the BSLIP template were at the border for stable skipping. It is possible that individual variation in GRF were related to differences in the angle of attack, like it is seen for skipping gait with perturbation [19].

For the wrap jump, again, in most cases hindlimbs touched the ground synchronously at take-off phase, but the hindlimbs were no longer acting similar. The peak vertical forces rose to a plateau and were higher for the right hindlimb than for the left hindlimb. Also, longer contact durations in both hindlimbs allow the generation of larger vertical impulses.

The inner hindlimb, in our case the left hindlimb, almost exclusively showed decelerative impulses, while the right hindlimb showed decelerative impulses only for the first half of the contact period and then changes to accelerative impulse. This behavior has a characteristic like a differential gear and resulted in a torque which make the dog starting the wrap already at the take-off phase. This mechanism works only when the dogs previously known direction of jumping.

At landing, both forelimbs touchdown almost synchronously. After touchdown, right forelimb takes off bevor left forelimb takes off. Right forelimb shows higher peak vertical forces, maximum is reached at nearly 30 % of stance. Significantly longer contact times would in theory allow spreading of force production over a longer time and thus lead to reduce peak vertical force, which could lead to reduces stress in bones. A doubling of the contact duration in comparison to straight jump would imply slower speed. Possibly, dogs had to compromise between speed, and stress in bones. Both forelimbs showed breaking forces during the most part of the contact phase. Additional higher mediolateral force in the right forelimb than in the left forelimb, show that dogs would have to work against inertia effect to change direction.

Mostly agility courses are consisting more wrap jumps than only straight jumps. The internal structures of the locomotor system must deal with these repeatedly, and that this might contribute to the higher risk of injury in agility dogs [3].

5. CONFLICT OF INTEREST STATEMENT

None of the authors has any financial or personal relationships that could inappropriately influence or bias the content of the paper.

6. ACKNOWLEDGEMENTS

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